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Embouchure muscle activity in student and elite trumpeters; a pilot study.

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Abstract

Aims. Objective information on embouchure muscle use in brass players is currently limited. This pilot study records and analyses embouchure muscle activity in trumpet players to identify typical patterns and to reveal how these can differ between playing tasks

Method. Activity in four embouchure muscles was recorded using surface electromyography in 7 conservatoire trumpet students and 3 elite professional trumpeters. Each played a set of simple exercises, tongued and slurred, including single notes of different pitch, upward and downward transitions between notes a fifth apart, arpeggios and a short musical piece.

Results. Muscle activity was initiated 0.4-2.0s before the beginning of a note. In some players this was at a higher level than needed to sustain the note, while in others it was not. Levels of activity in all muscles generally increased and decreased together during arpeggios, in line with changing pitch. The sound was terminated by an abrupt fall in muscle activity. In many players, transitions between notes a fifth apart required no change in muscle activity though in others this was marked by a sharp increase or decrease.

Conclusion. Though levels of muscle activity rose consistently over large pitch ranges, there was considerable variation in the degree to which this occurred over smaller intervals. Even among the three professional players, the embouchure muscle activity showed clear individual patterns, suggesting that high levels of performance can be achieved in different

ways. Further investigations will be needed to clarify how embouchure activity changes with proficiency.

Introduction

In the context of brass performance, the embouchure can be defined as the lip conformation created by action of the facial muscles and supported by the teeth and jaw [1]. The central element is the orbicularis oris, the purse-string muscle surrounding the oral aperture. Muscles that raise and lower the corners of the mouth (levator and depressor anguli oris, zygomaticus and risorius muscles) interdigitate with the orbicularis oris at the modiolus, a fibrous thickening of its lateral regions. The elevators and depressors of the lips (levator labii superioris and depressor labii inferioris muscles) also interlace with orbicularis muscle fibres. Below the central region of the lower lip is the mentalis muscle which contributes to pouting movements. Together these form a muscular framework that can be used to manipulate the tension and shape of the lips [1,2]. The muscular wall of the cheek is formed by the buccinator muscle whose fibres merge with orbicularis oris muscle anteriorly. Posteriorly it fuses with the superior constrictor muscle of the pharynx via the pterygomandibular raphe. The pressure generated in the upper part of the airway during brass playing is therefore contained within a continuous muscular tube.

There have been only a few studies of lip movement within the mouthpiece during brass playing. This varies between individual players depending on playing style (an active component) and level of experience [3] as well due to differences in orofacial structure including the mass of the lips [4] (a passive component). There are also differences between instruments linked to the dimensions and shape of the mouthpiece. Studies of a small number of French horn players suggest that there is much greater movement in the upper lip than the lower one in this instrument [3]. This has yet to be examined in detail in the trumpet, but stroboscopic video evidence suggests that the difference between upper and lower lip excursion in the trumpet may be less extreme [5]. However, larger numbers of players of both instruments need to be studied to confirm this. As a result, patterns of embouchure-related muscle activity may vary not only between players of different brass instruments, but also between proficient players of the same instrument.

Though there have been a number of electromyographic (EMG) studies of activity of the embouchure muscles in brass players, these have been rather unsystematic. Most date from a time before computerization made it straightforward to quantify EMG data. The majority of these studies were on the trumpet [6-13], though more recently normal [14,15] and dystonic [16] embouchure muscle activity has been examined in French horn players. The most comprehensive study of embouchure to date is that of Basmajian and White [10-12] who posed a number of specific questions of relevance to brass teaching and technique through a comparison of muscle recordings from players of different levels of expertise. However, many aspects of the experiments and their analysis were not adequately defined and no actual EMG recordings were shown. In addition, due to the limitations of the technology of the time, levels of EMG activity were only estimated by eye to produce a semi quantitative assessment of activity. The design of the current study is based to some extent on that of Basmajian and White [10,11] as the central question they sought to answer is still relevant to brass players; i.e. are there consistent patterns of activity associated with different playing tasks. They also sought to determine if there are particular patterns of embouchure activity that young players should aspire to because they are correlated with high levels or performance. To achieve this aim it is first necessary to collect information from a number of players at different levels to understand the level of variability that can exist between them. We present results from seven student players and three professionals and examine the similarities in the patterns their embouchure muscle activity as well as their individual characteristics.

Methods

Subjects

Seven second-year trumpet conservatoire students at the <BLINDED> College of Music and Drama (<BLINDED>) - entrance requires a playing level of Grade 8 or above) and three professional trumpet players, were offered the opportunity to volunteer as participants in the study. All participants were required to be in good respiratory and physical health for brass playing, and no subjects were excluded on this basis. One elite trumpeter reported complaints of air leakage via the lips. The seven trumpet students had a mean age of 21.8 ± 1.1 years (range 19-22), and the three professional trumpeters were aged 30, 36 and 48yrs. All of the professionals are elite musicians who play in internationally acclaimed orchestras and ensembles. All experiments were carried out with informed consent and according to the Helsinki declaration, and were approved under the local ethical procedures of the School of <BLINDED> University. The players used their own instruments and mouthpieces.

Electromyography (EMG)

Muscle activation was recorded using 9mm diameter electroencephalography (EEG) electrodes, because of their small size and the lightness of their connectors and cables. After the skin was cleaned with alcohol, pairs of silver/silver chloride EEG electrodes were attached approximately 2cm apart, parallel to the estimated direction of the muscle fibres. They were injected with One-Step EEG gel (Unimed, Farnham, UK). The EEG electrodes were attached with double-sided adhesive tape rings. The cables were supported by a headband. It was possible to record from four muscles on each side of the face and still allow unobstructed positioning of the mouthpiece (Fig. 1). Two webcams provided digital video recordings of the front and side of the face that could be replayed in in synchrony with the EMG traces. EMG recordings were made from the orbicularis oris muscles in the upper and lower lips (which form the central element of the embouchure), the zygomaticus and the depressor anguli oris muscles. They were chosen because they lie superficially, enabling recording with surface EMG and include the muscles at the core of the embouchure and those outside the lips that regulate their tension and raise or lower the corners of the mouth.

Electrode placement was determined using criteria indicated by Lapatki [17,18]. A ground electrode was placed over the spinous process of the seventh cervical vertebra. EMG signals were passed through CED 1902 amplifiers connected to a CED 1401 A/D converter (Cambridge Electronic Design, Cambridge, UK). They were sampled at 1kHz and displayed and analysed using Spike2 software (Cambridge Electronic Design, Cambridge, UK) which could also replay the synchronised video files. A high band pass filter (90Hz) and a 50Hz notch filter were used to eliminate movement artefacts and electrical interference. The raw EMG traces were processed using a root mean square (RMS) algorithm with a time constant of 100ms. To investigate the possibility of cross-talk, a simple rectification was used to preserve the detailed temporal structure of the signals. Sound was recorded using a Shure C606 microphone placed 1m from the player. The signal was passed through an SP-24B preamplifier (Maplin, Rotherham UK) and then to the CED 1401. Sound could be displayed as a voltage trace (reflecting sound volume) or as a sonogram so that muscle activity could be correlated with the beginning and end of notes and their pitch. Descriptive statistics and paired t tests were carried out using Excel (alpha = 0.05).

Musical tasks

The musical tasks were selected to provide unambiguous information on core elements of brass playing and were relative easy to perform in relation to the abilities of the participants. The timing was regulated with a metronome at crochet = 60 beats per minute. The playing tasks were a) single notes (semibreve) at two pitches (concert middle C and the G above); b) upward and downward intervals between minims a 5^{th} apart, tongued and slurred (C to G or G to C); c) a two octave arpeggio starting on middle C tongued and slurred and finally d) a short piece of music (the theme from Bach's Goldberg Variations, which covered the same range as the arpeggio) played tongued and slurred. All tasks were repeated 3 times with rests between except for the Bach theme which was played once. Players were asked to perform at *mezzo forte* throughout. Some variation in sound intensity during playing of for example the Arpeggios and pieces of music was unavoidable. It was therefore not practical to control for intensity completely. Recordings were also made of maximum voluntary contractions (MVC) from facial grimaces such as pressing the lips together, pouting, drawing the corners of the mouth strongly up and down. Unlike other muscles for which MVC is used, those of facial cannot be held isometric or be performed against a load. Another way of obtaining a standard against which to measure muscle activity is to use the maximum value seen during the experiments [19]. In our study, that always occurred on the top note of the two octave arpeggio which we here call maximum recorded activity (MRA). Except for one muscle in one professional player, this was always considerable greater than MVC. Averaged across all the muscles MRA was 119.5% $\pm$ 20.8% (mean $\pm$ s.d.) of MVC for professionals and 118.5% $\pm$ 14.4% of MVC for students. In the Results section we used MRA as the reference when analysing the data, however this has certain implications for interpretation which we review in the Discussion.

Results

Making statistical comparisons between student and professional players was not feasible for a number of reasons. First, the students had had many years of formal instruction (typically around 10) but nevertheless were at quite different stages of technical development. Some students go straight from the conservatoire to leading orchestral positions and so may be close to professional standard while others are less advanced. They are therefore not a homogenous group. Secondly, the three professionals each showed a unique pattern embouchure muscle activity. Thirdly, the sample size was very small.

Cross talk between muscle recordings

Because embouchure muscles lie in close proximity, the possibility of cross-talk must be considered. Comparisons of the recordings from the muscles shown in Fig. 2 demonstrate that it is possible to obtain signals with little if any cross-talk.

Exercises

Single notes

The embouchure muscles generally contract rapidly before the onset of the note. For isolated single notes this is typically 0.4-2.0s before the sound is initiated (Fig. 3). During the note, the activity shows small fluctuations around a relatively constant value until it ends as the muscles relax. This termination is often abrupt though how rapidly activity falls may vary from muscle to muscle even in professional players. In the examples show, this is less marked in the muscles of the lower lip and is more obvious in some players than in others.

Ascending and descending 5ths.

For this exercise, recordings from three professionals and five of the students are presented to illustrate the pattern and degree of variability there is between embouchure activity in different players. Muscle activity in slurred and tongued intervals between notes a fifth apart was measured by taking the mean during the note after any transient peak that marked note transition (see Figs 4-8). Such transients are seen only in some players and even then, not in all muscles. For the upward 5th from middle C to G, the mean increase in activity across all muscles and averaged across all players was 30.9% from the level of the lower note for the tongued transition and 36% for the slurred transition. A paired t-test comparing the tongued and slurred transitions for the muscles of each player found this to be statistically significant only for Professional 1 ($p=0.03$) and Students 1 ($p=0.03$) and 2 ($P<0.001$).

For the downward fifth, the mean fall in muscle activity from G, to middle C was 24.0% for the tongued transition and 22.8% for the slurred transition. There were no significant differences in EMG patterns between the tonguing and slurring for any player.

Professionals 1 and 2 show only small differences in mean activity between the two pitches in the upward and downward transitions (Figs. 4 and 6). By contrast, Professional 3 shows a noticeable increase with rising pitch and decrease with falling pitch in the activity of several muscles. However, for the right orbicularis oris of the lower lip the activity instead goes in the opposite direction to the pitch change. Some students (especially Students 2 and 4) show large and abrupt changes in the activity of all muscles with rising and falling pitch (Figs. 5 and 7). This is not seen for Student 1, who maintains a very high level of muscle activity throughout all of the exercises for whom it is a feature of personal playing style.

Fig. 8 compares the changes in muscle activity for the rising and falling 5ths for each player. The total height of each column indicates the change between the first note and the second in the slur. Within the columns the relative contribution of each muscle is indicated. For the rising 5^{th}, the three professionals and four of the students show an increase in activity between the first and second note of around 25%.For three of the students (S2, S4 & S6) this increase is much greater. In one (S4) the increase is around 80% (Fig. 8A). For the falling 5^{th}, the same three students show a much greater fall in activity than the other players (Fig. 8B).

For most players, transient pulses of activity at note transitions were either absent or small. However, for Professional 1, these were a feature of playing style and were sometimes present both on ascending and descending intervals (Figs 4, & 6). This was particularly marked in the depressor anguli oris muscle on both sides which appeared to play an important role in this player's control of pitch both here and in other exercises. These pulses were similar whether the exercise was tongued or slurred.

Two octave arpeggios

During the two octave arpeggio, activity in all of the muscles rises together with pitch in all players (Fig 9A,B & 10A). The mean level of activity across all muscles for middle C is 36.5% $\pm$ 5.1% of MRA rising to 94.5% $\pm$2.5% of MRA for the C two octaves above. There is no difference in the mean pattern of activity for upper versus lower lip (orbicularis oris superior and inferior (Fig 10B) or for muscles within the lips (orbicularis oris) compared to those outside the lip (zygomaticus and depressor anguli oris), (Fig. 10C). The data in Fig. 11 show the degree of symmetry of muscle activity on the left and right side of the embouchure for two professional and two student players. The traces from Professional 1 show a high degree of symmetry and also that there is a steeper rise in activity in zygomaticus and depressor anguli oris in the upper octave than for the lip muscles(upper and lower orbicularis oris). Though there are differences in the pattern of muscle activity in the ascending and descending phases of the arpeggio, symmetry is maintained in both phases. Muscle activity in Professional 3 (who reports problems with lip seal on the right side) is largely similar, except that the right zygomaticus is much more active than the left, particularly in the ascending arpeggio (arrow). The two student examples shown have largely symmetrical activation in most muscles except for zygomaticus in Student 6 (arrow). The changes in activity with pitch are also less smooth in the student examples than in those of the professionals.

Individual variation is again seen in Fig. 9a. The professional shows the typical pattern in which muscle activity rises continuously over two octaves from a mean across all muscles of 39.1% $\pm$ 5.8 MRA for middle C. In student 1, mean muscle activity is already 59.2 $\pm$ 10.0% for middle C, so that the increase over the two octaves is much less. The pattern of muscle activity individual players remained consistent when the exercises were repeated. .

In most players there is little difference in the pattern of muscle activity between slurred and tongued arpeggios. Where there is a difference, this takes the form of more marked fluctuations in activity between notes during tonguing (Fig. 9b).

Bach theme

The Bach theme provides a more representative example of embouchure activity during actual performance but, because of the constant changes in pitch direction and note duration, it gives less information on individual elements of technique (Fig 12). The theme has two phrases, the second of which is more demanding because it rises higher in the range. In most players, muscle activity during the first phrase is relatively constant while for the second, the levels more closely match the changes in pitch (e.g. Professional 2 in Fig. 12). However, the pattern is different in Professional 1 who, as previously described, made particular use of depressor anguli oris muscle for pitch control in the 5th interval transitions. Similar use of this muscle (but not the others) is made in the relatively low first phrase of the Bach. In the more demanding second phrase, all muscles work in unison; a pattern that is typical of the other players.

Discussion

Limitations of Measuring levels of muscle activity.

The levels of the surface EMG recordings cannot on their own be used as an estimate of the absolute force generated by a muscle as the amplitude of the signal is affected by parameters such the conductivity of the skin and subcutaneous fascia, the precise placing of the electrodes over the muscle and how this relates the positioning of the motor end plates [20,21]. Motor end plates are scattered in some facial muscles such as orbicularis oris and eccentrically clustered in others, for example in the depressor anguli oris[17,18] and their small size limits the options for electrodes placement. Maximum voluntary contraction is often used to provide a reference for the level of activity seen during the behaviour under investigation. For MVC, the muscle contractions used are usually isometric and carried out under load. It is not possible to load the muscles when using facial expression as test actions but it has been suggested that contraction of the embouchure muscles during brass playing is essentially isometric [14]. Furthermore, it has been noted that MVC has never been validated as a reliable standard for facial muscles [15]. Even for muscles elsewhere in the body, voluntary effort cannot be completely standardised. The main reason for attempting MVC measurements on embouchure muscles despite these difficulties was as a means of determining whether activity during brass playing was symmetrical. As the facial expressions generally appeared to be symmetrical, it would be expected that the level of muscle activation would also be similar on each side of the face. In professional player P3 maximum activity of the zygomaticus muscle in the arpeggio was 221% of MVC on the right side but only 55% on the left. This could be interpreted either as an indication that the right zygomaticus is much more active than the left at low pitches or, as it increases less for the upper range. However in the other professionals, differences of between 25 - 50% of MVC were seen between individual muscles on the left and right side and similarly large discrepancies were found in all but one student. This either means that asymmetry of activation during playing is almost universal, or that MVC of facial muscles is an unreliable standard. Direct measurements of the force that can be generated by the muscular wall of the cheek (predominantly buccinator) in trumpeters has revealed differences of up to 25% between the left and right side [22]. As we were not able to measure muscle force directly, we could not rely on MVC as a marker for absolute levels of activation. We therefore used MRA as a standard and compared the EMG traces of left/right muscle pairs during the exercises to determine whether the *pattern* of activation (if not the absolute level of activation) was symmetrical.

Patterns of muscle activity in brass players

Few studies have analysed embouchure activity in brass players across a wide range of playing tasks. The most comprehensive is one of the earliest, carried out by White and Basmajian [10-12] who compared players who were beginners with those who were more advanced. According to their definition however, all of our players are advanced. White and Basmajian used wire electrodes implanted into four embouchure muscles. These were the orbicularis oris of the upper and lower lip (superior and inferior), and the levator and depressor anguli oris muscles Other studies of embouchure function did not record from orbicularis oris but only from muscles outside the lips [6,7,13-15], though of these only Heuser and McNitt-Gray recorded from the same muscles on both sides. Unfortunately, only a few of the large number of tests used by White and Basmajian were described and no raw data was presented. The number and level of experience of the subjects was similar to our group except that it also included 5 school students and a non-music sophomore. This allowed the subjects to be divided into two clear groups based on level of experience for comparison.

Due to the limitations of the technology available at the time, the recordings were in the form of analogue signals recorded on tape and not digitised waveforms as is current practice, which facilitates quantitative analysis. EMG activity levels were estimated visually on a four point scale to allow some statistical analysis. Comparisons were made between muscles with no reference to any absolute standard so some conclusions are open to debate, however we will make comparisons with the results of this study as far as is possible.

Recordings of single notes played by trumpet and French horn players in other studies show a brief period of muscle activity before note onset, then a relatively constant phase during the note before activity abruptly falls in all muscles at its end [6,7,14,15]. This was true of our data though we found considerable variation in the duration and amplitude of activity immediately prior to the note. In line with White and Basmajian [10] we found that the majority of their players had their own distinctive pattern: e.g. for eight out of ten trumpeters the amplitude of pre-note activity closely matches that of the note itself but for two (S2 and P1) it did not.

Several studies relate that embouchure muscle activity increases with both pitch and volume in the trumpet [10,11,13]. The same is reported for the French horn though the data suggests that for pitch, activity in some muscles may increase more than others [14]. The smallest increase was for the horn players was in the levator labii superioris and zygomaticus muscles and greatest in depressor anguli oris and depressor labii inferioris. There is no equivalent published data for the trumpet, but our results indicate that though mean activity over two octaves rises similarly in all muscles, for any individual player the pattern can vary between muscles.

White and Basmajian [10-11] proposed that in advanced players there was greater activity in muscles outside the lips (in their case, levator and depressor anguli oris) than within them (orbicularis oris). They also noted that the level of activity in the upper and lower lips of advanced players was more similar than in their beginners group. These conclusions rest on the assumption that the absolute amplitude of the EMG signal reflects the degree of muscle contraction and can be compared between muscles. There is some evidence that, the relative size of the EMG signal is related to the degree of muscle contraction over most of the range [23]. However in order to compare levels of activity between muscles- this must be measured against some objective or semi-objective standard such as MVC or MRA. White and Basmajian did not do this. Furthermore any comparison will be affected by the relative strengths of the individual muscles which would be extremely difficult to determine. We therefore did not try to make such comparisons but looked at patterns of muscle activity using MRA as a reference. We found that over the range of the two octave arpeggio the mean incremental rise in activity for muscles inside and outside the lip were almost identical as were those in the upper and lower lip.

White and Basmajian[10,11] were interested in the relative activity of the muscles inside and outside the lip for two reasons. First, one concept that is prevalent among brass pedagogues such as Farkas [24], is that lip tension is controlled by a dynamic interaction between the muscles inside and outside the lip. Across our group of subjects, we found mean activity in all of the recorded muscles rises in parallel with pitch. This supports Farkas's contention, with the proviso that in individual players there may be differences between muscle groups with respect to where in the pitch range this increase is greatest. Secondly, there is a belief among some brass players that depressor anguli oris may play a particularly important role in the control of lip tension [25]. Observations on French horn players would be consistent with this idea[14]. However, like White and Basmajian[10] we found no evidence for this except for Professional 1, who did appear to use it to set the embouchure during pitch changes. This does not necessarily indicate that the corners of the mouth are not held down by our other subjects, only that the balance between the depressor anguli oris and zygomaticus muscles was being maintained with changing pitch.

White and Basmajian[10-11] report that their advanced players show a smaller range of variation in small interval lip slurs than the beginner group and equate this with pedagogical practice of keeping the embouchure still during pitch changes. They do not stipulate the size of the interval; neither do they indicate whether they examined transient activity at note transitions as well as comparing the levels underlying each of the two notes. Over tongued and slurred intervals of a 5th we found a mean increase in activity in the rising interval of 30-35% and a reduction with falling pitch of 22-24%. However, this was much larger in three of the students. Two of these were judged to be among the least experienced which would be consistent with the conclusions of White and Basmajian [10-11]. However this would not necessarily indicate greater movement of the embouchure if the activity changes in all embouchure muscles was balanced. We also looked at the smaller interval of a single tone (both tongued or slurred) and found virtually no change in muscle activity and only occasional small transients at the transition points. One notable difference between the professionals and the students was that when playing long notes, muscle activity in the professionals was very even whereas it tended to fluctuate up an down in the students (compare Figs. 4 and 6 with Figs. 5 and 7).

Individual variations between players

We have alluded in several places to the distinctive patterns of muscle activity characteristic of individual players. Variability in the amount of movement of the face during playing and the necessity to use different strategies depending on the structure of the face and lips has been noted by several brass pedagogues [26,27]. The three professional players in this study had quite different strategies (summarised in Table 1). Professional 1 plays primarily with a full symphony orchestra and had a sharp pinging attack and made strong use of depressor anguli oris muscle. Professional 2, who performs mainly on the cornet with renowned brass bands, had a more gentle attack and a similar pattern of activity in all of the recorded muscles. Professional 3 who performs with chamber orchestras and small ensembles, also played with a gentle attack. This player exhibited a clear left/right asymmetry in muscle engagement. Atypical activity was seen particularly in the right zygomaticus in the arpeggio task (Fig. 11), while the right orbicularis oris of the upper lip shows anomalous changes in activity during intervals of a 5th in the opposite direction to the pitch change (Figs. 4 & 6). All three professionals are elite level players so their strategies are clearly effective for them.

Among the students there is also a marked degree of variation between players though for this group it is necessary to consider the extent to which this may related to the level of technical development. Student 1 uses a much higher level of muscle activity (as expressed as a percentage of MRA) than all other players even for low notes. One consequence of this may be that changes in embouchure activity contribute less to pitch control pitch than in other players. Other mechanisms such as manipulation of air speed must therefore play a more significant role[1,28]. In the other students the most obvious differences were the size of activity changes over intervals of a 5th and the presence of prominent transient bursts of activity at the beginning of notes. While it is possible that these features are more common in less developed trumpet players, it would be premature to reach a definitive conclusion without studying a larger cohort of players. Furthermore, though there will be problems with embouchure use that need to be corrected, it is unlikely that there is a single ideal embouchure for all trumpet players. Differences in the shape or fullness of the lips and the structure of the face will all be critical factors. This could form the basis of future studies. When entering College, our student brass students are allocated an instrumental tutor from among local professional players. Care is take to match them with tutors who have a similar playing style at least in the first instance so that their natural style can be developed. One factor underlying this may be their pattern of embouchure activity.

Conclusions

Though several studies of embouchure muscle activity in trumpet and french horn players have been carried out over the last 40 years, few have presented detailed systematic information on the pattern of muscle use in different players carrying out a standard series of playing tasks. Our results show that while there are features common to most players e.g. an increase in activity in all of the muscles recorded with increasing pitch, there is also considerable variation not only within groups of students but also between professionals. While our preliminary results suggest that some features of embouchure activity may be related to playing proficiency, this needs further investigation with larger groups of players. The differences between professional players indicates that there is no single pattern of embouchure that is indicative of elite performance. The reasons for this are currently unclear but may include the way players have been taught, the style of playing they most engage in, and their facial structure. Further studies will be required to clarify the relative importance of these different factors which may have particular significance for how young players are taught.

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Figures

Figure 1. This shows the electrodes in position during a recording session. Their small size leaves adequate space for the positioning of the mouthpiece. The weight of the electrode cables is supported by a headband.

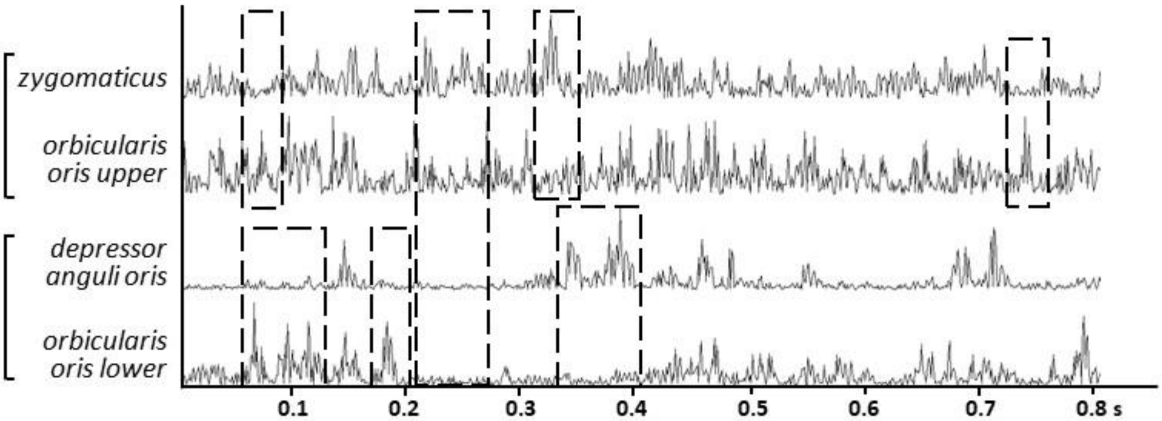

Figure 2.

Rectified waveform traces from the four recorded muscles from one side of the embouchure. The recordings of muscles closest together (and so most likely to show cross talk) are linked by the brackets. The boxes highlight sections of the traces where large features in one trace are not matched by patterns of activity in nearby muscles.

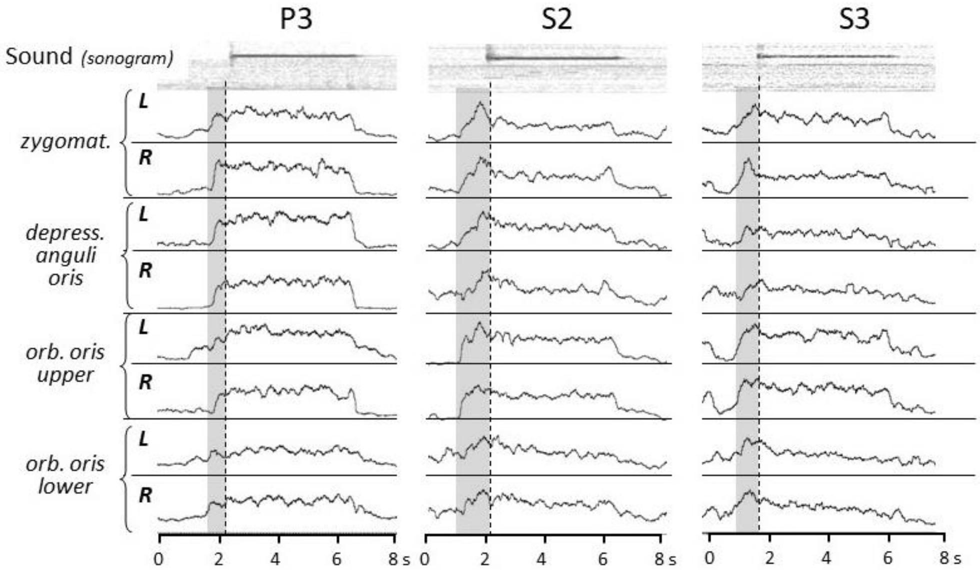

Figure 3

Muscle activity during single notes (G in the treble clef) played by Professional 3 (P3) and Students 1 and 2 (S1, S2). The EMG traces have been root mean square transformed and the first harmonic of the sound is shown a sonogram. The grey shading indicates muscle activity prior to note onset (dashed line). Zygomat, zygomaticus; depress, depressor; orb., orbicularis, L, left; R, right. The amplitude of the traces shown here and in later figures, has been optimised to make the pattern of activity as clear as possible and so are in arbitrary units.

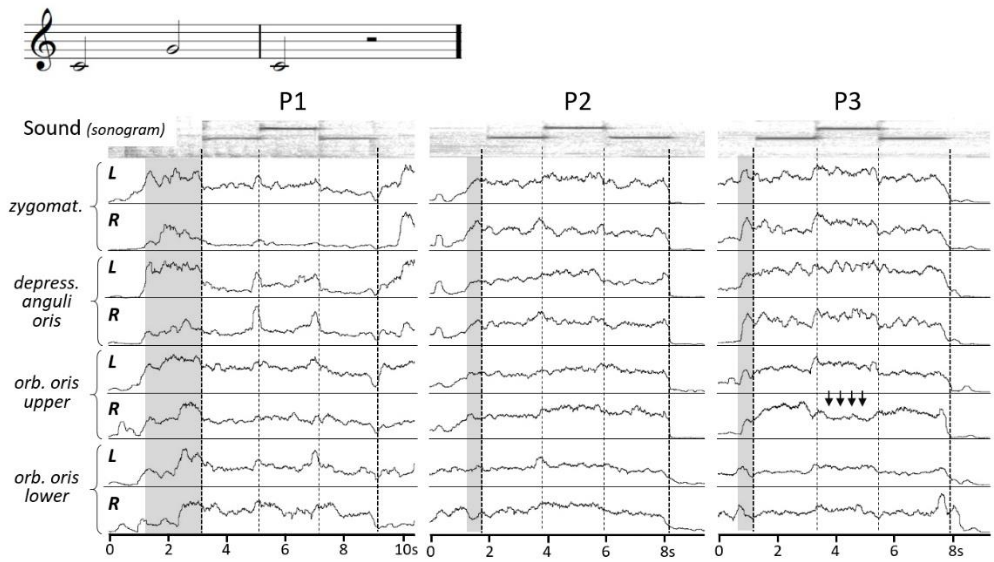

Figure 4

Muscle activity during upward then downward tongued 5ths played by the three professionals (P1-3) presented in the same format as Fig. 3.The grey shading indicates muscle activity prior to note onset (dotted line). Pitch transitions within the phrase are marked by the dashed lines. Note the strong transient bursts of activity in orbicularis oris at the beginning and end of the central G for Professional 1. For Professional 3, the rising pitch is supported by an increase in the activity of all muscles except for the right orbicularis oris where there is actually a fall in activity (arrows).

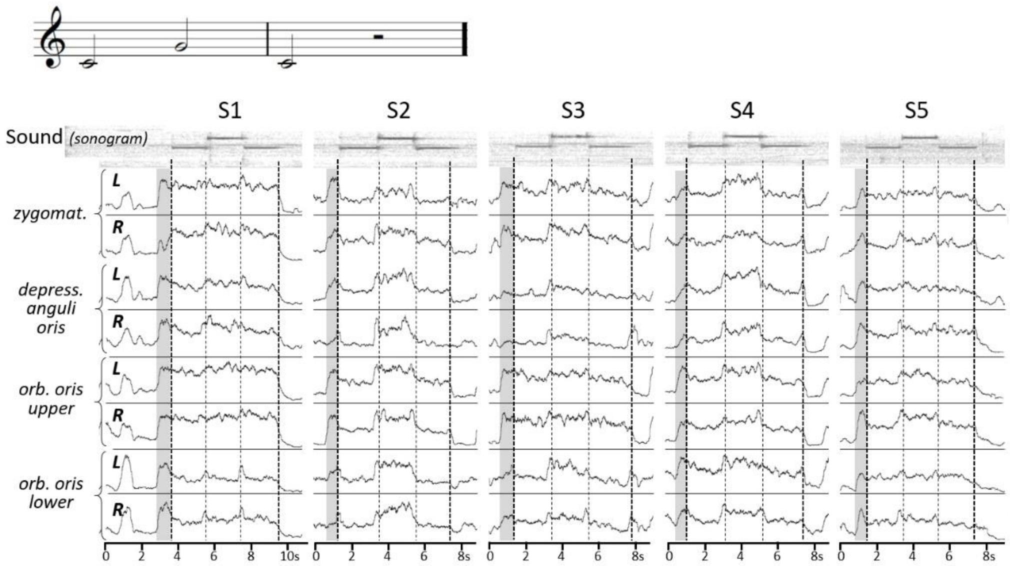

Figure 5

Muscle activity during upward then downward tongued 5ths played by the five of the student players (S1-5) presented in the same format as Fig. 3.The grey shading indicates muscle activity prior to note onset (dotted line). Pitch transitions within the phrase are marked by the dashed lines. Note the marked increase in the activity for the central G some or all muscles in students 2-5.

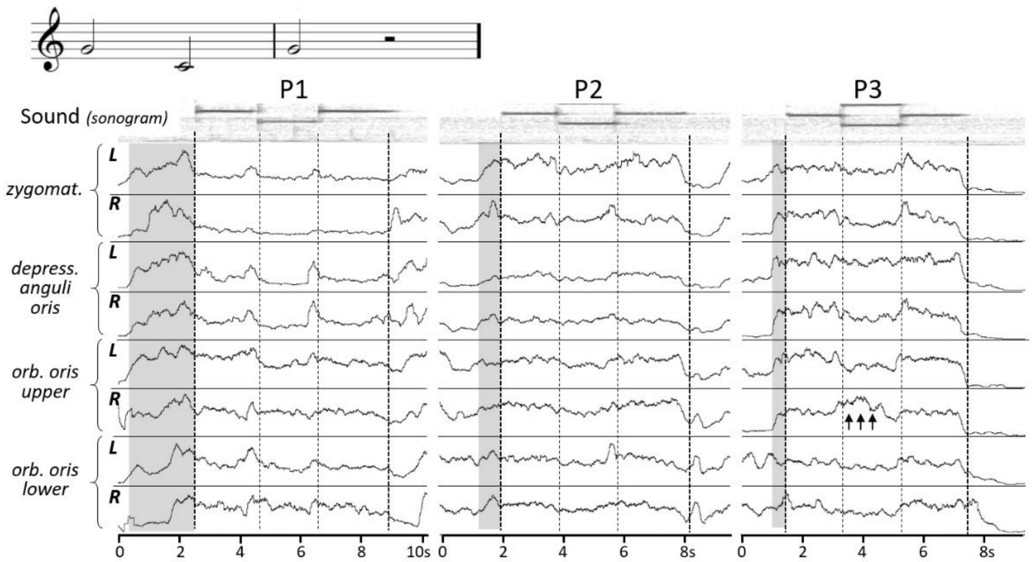

Figure 6

Muscle activity during downward then upward tongued 5ths played by the three professionals (P1-3) presented in the same format as Fig. 3.The grey shading indicates muscle activity prior to note onset (dotted line). Pitch transitions within the phrase are marked by the dashed lines. Note the strong transient bursts of activity particularly in orbicularis oris at the beginning and end of the central C and the small transients in some other muscles in Professional 1. For Professional 3, the falling pitch is supported by an decrease in the activity of several muscles but for the right orbicularis oris, where there is a rise in activity (arrows).

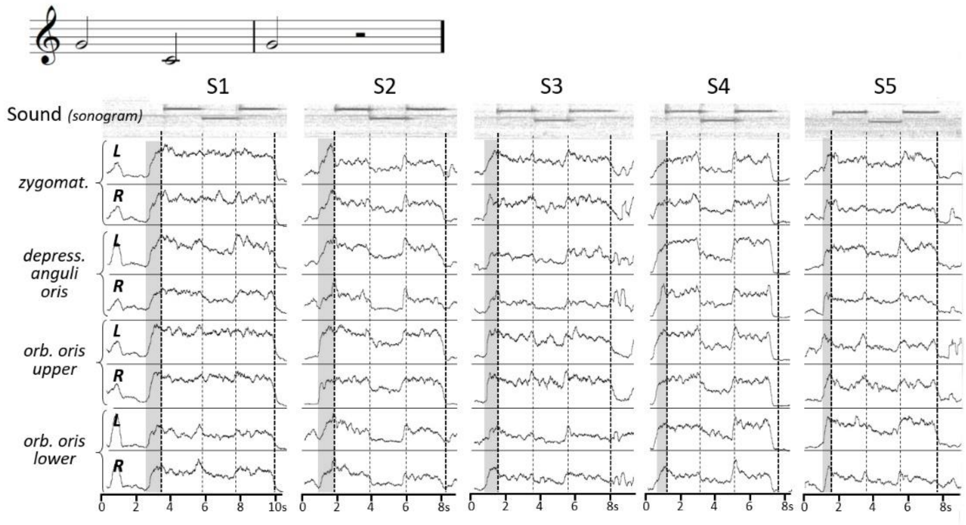

Figure 7

Muscle activity during downward then upward tongued 5ths played by the five of the student players (S1-5) presented in the same format as Fig. 3.The grey shading indicates muscle activity prior to note onset (dotted line). Pitch transitions within the phrase are marked by the dashed lines. Note the decrease in the activity for the central G for some muscles in all students. This is particularly marked and consistent for students 2 and 4.

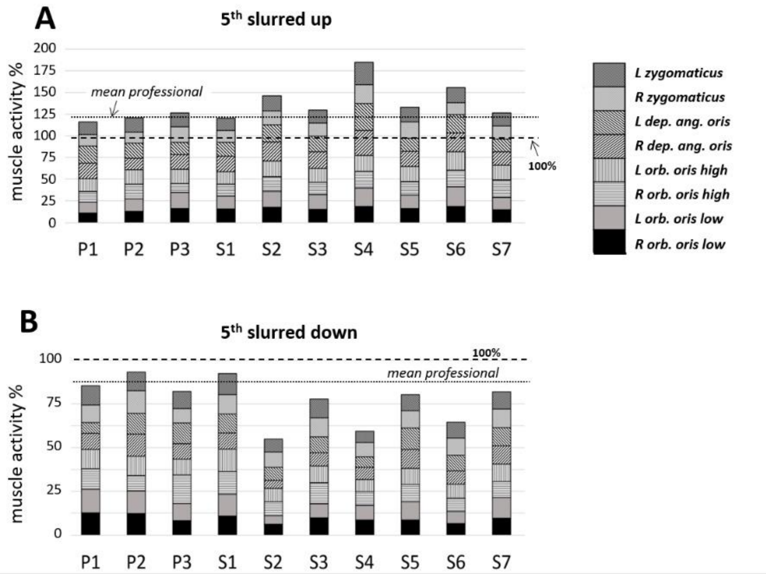

Figure 8

Bar graphs show the difference in activity between the first and middle notes in slurred upward and downward 5ths in both the professionals (P1-3) and all students (S1-7). The sum of the level of activity in all muscles for the middle note is expressed as a percentage of the level for the first note (which is designated 100%; dashed lines). The change for each individual muscle is indicated by the height of the relevant box within the column. For example in A the muscle showing the greatest increase for student 4 (S4) is the left depressor anguli oris. The dotted lines indicate the mean percentage for the professional players. Note that students 2, 4 & 6 show particularly large increases for the upward 5th (**A**) and particularly large decreases for the downward 5th (**B**).

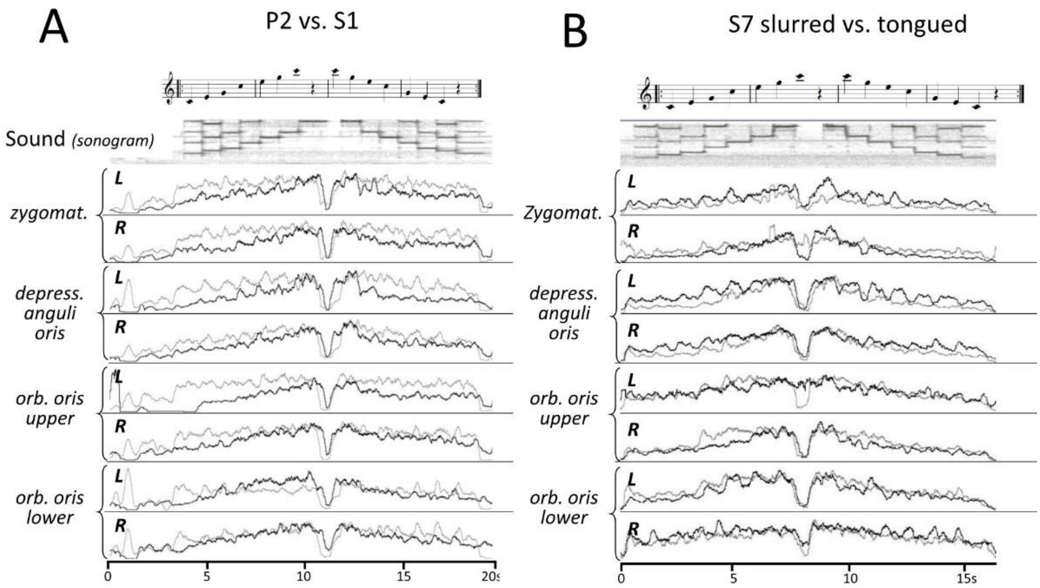

Figure 9

Muscle activity during the two octave arpeggio. **A**. Tongued arpeggio. A comparison between Professional 2 (P2; black trace) who shows a gradual increase in activity with pitch typical of most players, and Student 1 (S1; grey trace), who for several muscles uses a high level of activity regardless of pitch. **B**. A comparison of arpeggios played tongued (black) and slurred (grey) by student 7. In the tongued condition, there are more marked fluctuations in activity between notes in several muscles.

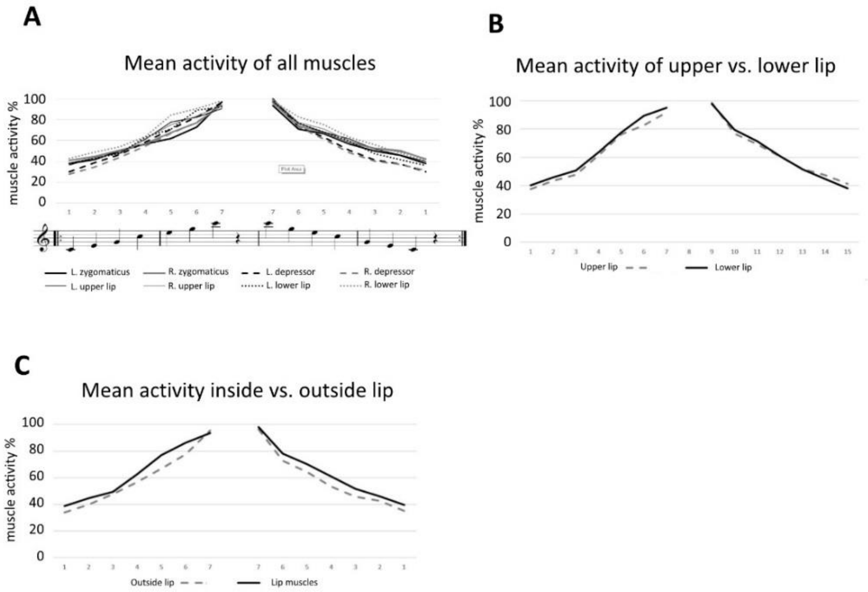

Figure 10

Comparisons of muscle activity over the two octave arpeggio. **A**. Mean activity in each muscle across all players showing that this rises similarly in all muscles. **B**. The muscles of the upper and lower lips (upper and lower orbicularis oris) rise together with pitch. **C**. Muscle in the lips (orbicularis oris) and outside the lip (zygomaticus and depressor anguli oris) show a similar pattern of activation with pitch.

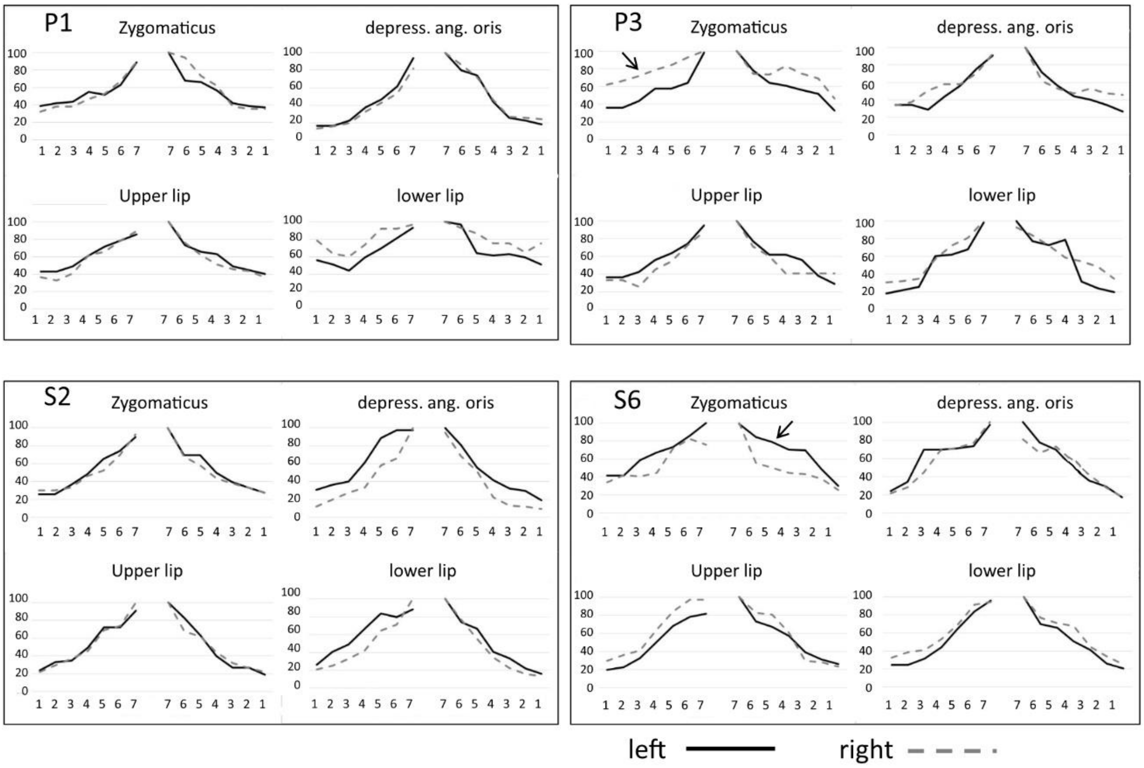

Figure 11

Comparisons of the same embouchure muscle on the left and right sides in the two octave arpeggio in two professional (P1 & P3) and two student (S2 & S6) players. Many of the traces show close symmetry but some reveal clear asymmetrical activation. This is most marked for zygomaticus in professional 3 and in student 6(arrows). The y-axis represents muscle activity as a percentage of the maximum seen in the arpeggio.

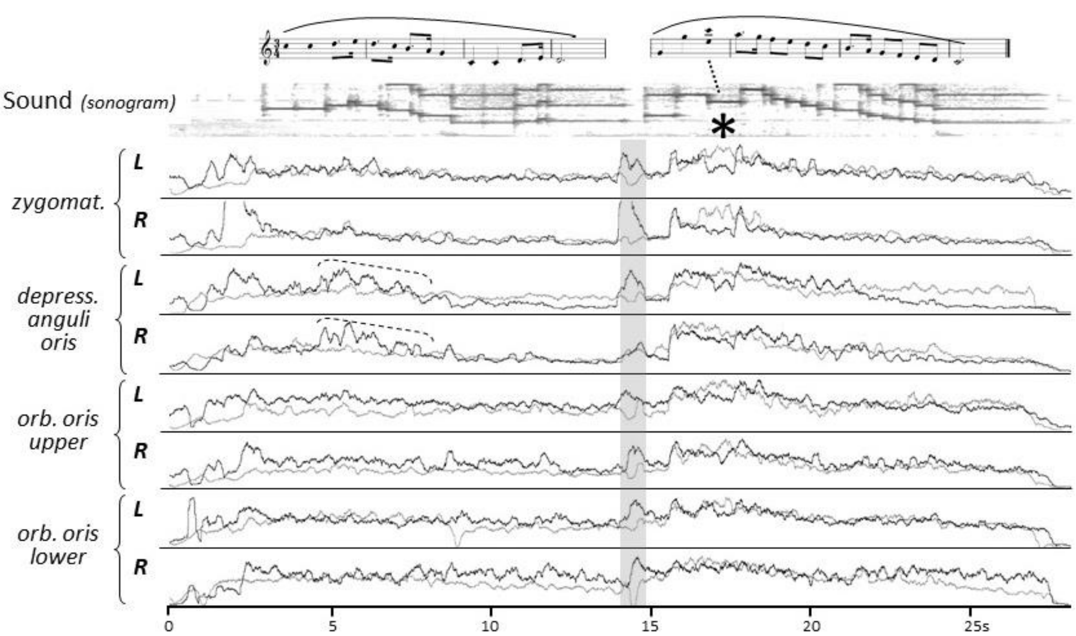

Figure 12

Muscle activity when playing the Bach theme in Professional 1 (black) and Professional 2 (grey). There is little fluctuation with pitch during the first phrase except for depressor anguli oris in Professional 1 (dashed bracket). Note that in the second phrase, this player plays an E rather than the C above at the point indicated by the asterisk (see musical notation) which explains the lower level of activity at that point (particularly clear for zygomaticus).

	Professional 1	**Professional 2**	**Professional 3**
Muscle activity prior to note onset	Long (1-2s) and at a much higher level than during the note	Short (0.5-1s) and at a similar level as during the note	Short (0.4-0.8s) and at a similar level as during the note
Attack	Hard, with sharp pinging onset	Gentle attack	Gentle attack
Time to reach max. sound volume	30-40ms	150-300ms	150-300ms
Pattern of muscle activity	Transient activity mainly in depressor anguli oris muscle during pitch changes	Muscles act in unison during pitch changes	Muscles act in unison in upper register but less so for lower register
Symmetry of muscle activity	Symmetrical	Symmetrical	Some asymmetry
Muscle activity during notes a 5th apart	Little change or no difference in activity sustaining the two pitches	Little or no difference in muscle activity sustaining the two pitches	Activity changes in direction of pitch change except right orbicularis oris whose activity changes in the opposite direction

Table 1. A summary of some of the major differences in the sound quality and embouchure muscle activity in the three professional players studied